Towards better design and management of tsunami evacuation routes: a case study of Ao Jak Beach Road

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Abstract: Among the thousands of people killed or reported missing in Thailand during the 2004 Indian Ocean Tsunami were villagers in small communities on the Andaman Coast. A combination of factors contributed to loss of life, including the lack of defined evacuation routes. This vulnerability to tsunami attacks has recently been addressed with the demarcation of evacuation routes, along both well-maintained arteries and native surface (unpaved) roads. However, poor location design and irregular maintenance will reduce the lifetime that the latter can provide safe egress from remote coastlines. In this work we identified 10 major gullies and 18 landslides along a critical 0.5 km section of a tsunami evacuation road accessing a remote beach of the Andaman Coast in southern Thailand. Erosion rates from landslides and gullies approached 9500 Mg ha^{-1} in less than a year following widening of the road. Importantly, the degradation features, landslides in particular, reduced the effectiveness of the road to serve as a safe passageway to escape future tsunamis or large storm surges. This study demonstrates that greater attention should be given to appropriate road location, design and maintenance in integrated programmes aimed at reducing tsunami vulnerability in remote coastal areas, not only on the Andaman Coast, but worldwide.

A magnitude 9.1 earthquake off the NW coast of Sumatra early in the morning of 26 December 2004 generated a deadly tsunami that reached the coastlines of 14 Indian Ocean countries, killing an estimated 230 000 people and displacing almost two million more (Ziegler *et al.* 2009; USGS 2010) (Fig. 1a). The highest death toll was near the epicentre in Aceh (Sumatra), where 180 000 perished; and casualties from as far away as Africa were reported (Guerena-Burgueno *et al.* 2006; Obura 2006). In Thailand, more than 5000 died and thousands more were reported missing (Guerena-Burgueno *et al.* 2006). Most of the victims in coastal Thailand were tourists, but many villagers in small communities along the Andaman Coast also perished (Birkland *et al.* 2006; Rigg *et al.* 2008). A combination of factors are likely to have contributed to the loss of life on the southern coasts of Thailand, including insufficient early warning systems, poor education regarding tsunami risks, destruction of natural ecosystem defenses by human activities and the lack of defined evacuation routes leading from coastal waters to safe zones at higher elevations (Charnkol & Tanaboriboon 2006; Cochard *et al.* 2008; Srivichai *et al.* 2009).

Reducing tsunami vulnerability has been a priority since the 2004 disaster (Rigg *et al.* 2005; Calgaro & Lloyd 2008). New evacuation routes, for example, have been established in many high-risk coastal areas in tsunami-prone areas of southern Thailand (TAT 2010). Most were established along well-maintained roads already in existence; however, in some cases native surface (unpaved) roads have become designated evacuation routes, especially for remote coastlines. Unlike paved roads near population centres, low-volume roads in developing areas are typically located with little regard for stability and they are often poorly designed and maintained, thereby reducing the lifetime that they can provide safe egress (Sidle *et al.* 2006). Only limited attention has been given to roads in the post-tsunami literature, with most given to road and bridge damage; others comment on the distances that must be traversed before reaching safety (e.g. Edwards 2004; Ziegler *et al.* 2009). Herein, we measure erosion and landslide features on a recently improved tsunami evacuation road in

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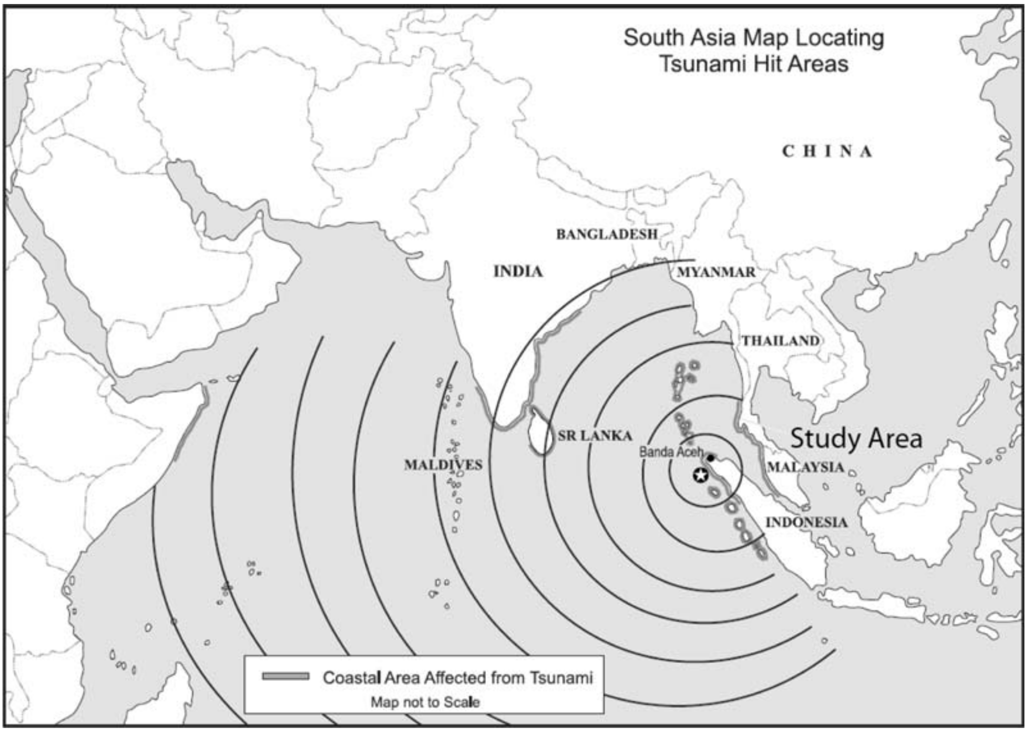

Fig. 1. Study area on the Andaman Coast of Thailand. The epicentre of the 2004 Indian Ocean Tsunami is shown (star). Map credit: Lee Li Kheng.

an attempt to understand how poor construction and irregular maintenance have reduced its effectiveness in providing long-term safe egress.

Study area

The Ao Jak Beach Road in the Suksamran District of Ranong Province, Thailand, accesses a remote coastal area where farmers and fishermen outnumber tourists (Fig. 1). The road replaced a narrow native surface track following the 2004 tsunami, which claimed the lives of several residents of nearby villages who failed to escape inland. In the latter part of 2009, the road was widened to improve accessibility to the coast, thereby reducing vulnerability to future tsunamis (Fig. 2a). Currently, the road is primarily used by local villagers to access fields, orchards and fishing spots. Tourists are beginning to use the road to access a remote beach and a few sparsely located bed and breakfast lodges. Vehicle traffic is largely restricted to motorcycles and small pickup trucks.

Ideally, a balanced cut-and-fill construction approach is desired to increase the operational road width and promote slope stability (Fig. 3a). Such an approach requires the excavated material to be carefully incorporated and compacted into the outer portion of the road prism (Fig. 3a). However, material excavated from the hill-slope during widening of the Ao Jak Beach Road was simply pushed to the outer side of the road prism where it created a berm, as well as a bed of unstable material on the fill-slope (Figs 2a & 3b). Some of the excavated material was incorporated onto the running surface of the road; other material remained near the cut-slope and some was eroded down-slope (Fig. 2). In general, no provisions were made for managing road drainage. Runoff water flowing on the road surface or within the inside ditch of the road prism was allowed to exit onto fill-slopes, which were inadequately prepared to receive runoff.

The impact of the widening process on the Ao Jak Road was akin to new construction, especially with respect to cut-slope stability. This manner of construction is common in locations throughout SE Asia where funding is limited. Excavating into the fractured and sheared sandstone bedrock over-steepened and removed support at the cutbank, destabilizing the upper hill-slope. Consequentially, in less than 1 year, many types of slope failures occurred on both the cut-slope and in the fill

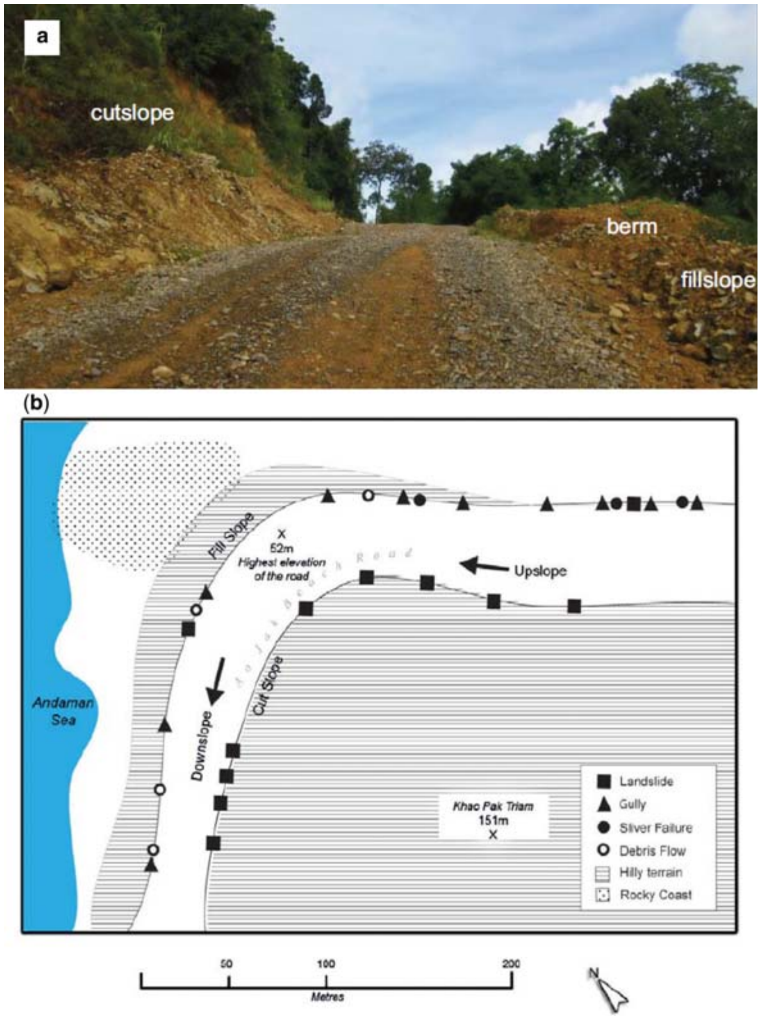

Fig. 2. (**a**) Crest of the Ao Jak Beach Road. Coarse gravel has been placed on the surface to improve traction. Unconsolidated material forms a berm on the fill-slope (right-hand side) after being excavated from the cut-slope (left). (**b**) Location on the Ao Jak Beach of observed landslides (boxes); debris flows (hexagon); sliver failures (circles); and gullies (stars). The road width is not drawn to scale.

materials; and gully erosion was prevalent on the fill-slope.

Ranong is the wettest province in Thailand – five of the wet-season months have a mean monthly rainfall of more than 500 mm (Table 1). Thus, the potential for surface erosion and mass failures in the area is very high (Degraff 1990; Phien-Wej *et al.*1993). The failures we observed on the Ao Jak Road were not caused by unusually large storms, rather by relatively small rain events between November 2009 and June 2010. The 967 mm of rainfall during this 8 month period is only about a quarter of the annual mean (Table 1).

Measurements

In June 2010, we mapped gullies and slope failures on a critical 0.5 km road section that rises to about 50 m above the beach (Fig. 2b). The mean (± 1 SD) width of the road was 7.3 $\pm$ 2.3 m ($n = 25$); the mean road slope was 7.3° $\pm$ 2.6° ($n = 25$). Three types of slope failures were identified: landslides on both cut-and-fill slopes, debris flows; and sliver failures (Fig. 4). Sliver failures are shallow slides in loosely or uncompacted fill material deposited on steep slopes (Sidle *et al.* 1985). The volume of material mobilized by most of these processes

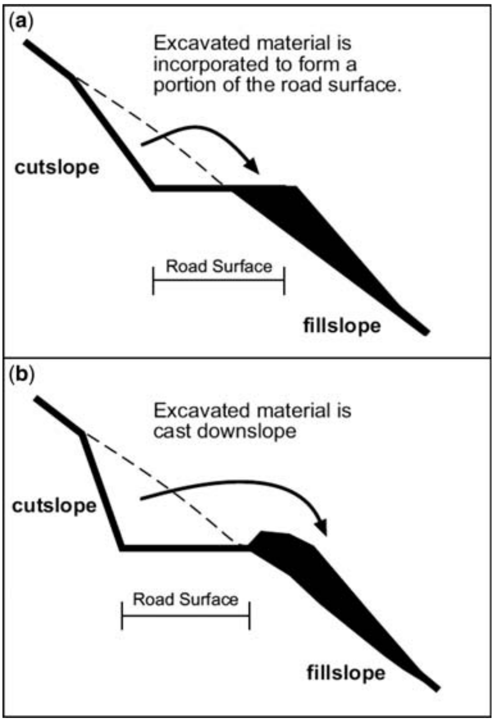

Fig. 3. (**a**) A balanced cut-and-fill road construction technique that incorporates compacted, excavated hill-slope material into the fill-slope to form a substantial portion the road width. (**b**) During road widening at Ao Jak, excavated material was side cast onto the fill-slope rather than being incorporated into the design of the operating portion of the road (adapted from FAO 1998).

was determined by estimating the volume of the geometrical shape of the deposited material (e.g. trapezoid, triangle or rectangle). In cases where the material had been eroded away, the scars were measured. Because we were interested in processes that were immediately threatening road accessibility, we did not quantify total erosion on the entire road prism. For example, we were unable to quantify the chronic process of road surface erosion by overland flow because it was greatly altered by the recent addition of coarse gravel to improve traction on steep sections.

Results

The survey revealed 10 gullies and 18 slope failures that amounted to a total of 2664 m^3 of material mobilized along the 0.5 km stretch of road (Fig. 2b; Table 2). Mass-wasting processes (landslide, debris flows and sliver failures) comprised nearly 98% of the volume of material displaced. Only about 2% of the sediment loss was attributed to gully erosion. There was no discernable relationship between drainage area and erosion or slope failure features (cf. Montgomery 1994). The gravel surfacing may have limited gully formation on the running surface but it did not prevent gullies from forming on other parts of the road prism.

Landslides represented the largest volume of displaced material (2178 m^3). Eight of the 11 landslides occurred on hill-slopes steeper than 40° (Fig. 5). Most of the landslides were shallow debris slides that were initiated during rainfall events. These slides were characterized by a distinct scarp at the head, a translational failure plane and a

Table 1. *Mean (1961–1990), 2009 and 2010 rainfall for Ranong Province (TMD 2010)*

	Long-term mean		2009		2010	
	Rainfall (mm)	No. of days	Rainfall (mm)	No. of days	Rainfall (mm)	No. of days
January	19	4	10	1	31	5
February	13	3	0	1	10	4
March	34	5	141	18	46	6
April	140	12	305	20	30	6
May	513	23	586	27	307	24
June	734	26	778	26	454	26
July	654	27	809	24	615	27
August	809	28	684	27	615	27
September	675	26	641	23	296	21
October	393	23	360	21	540	26
November	165	15	74	10	211	18
December	38	7	15	5	162	11
Total	4187	199	4405	203	3315	201

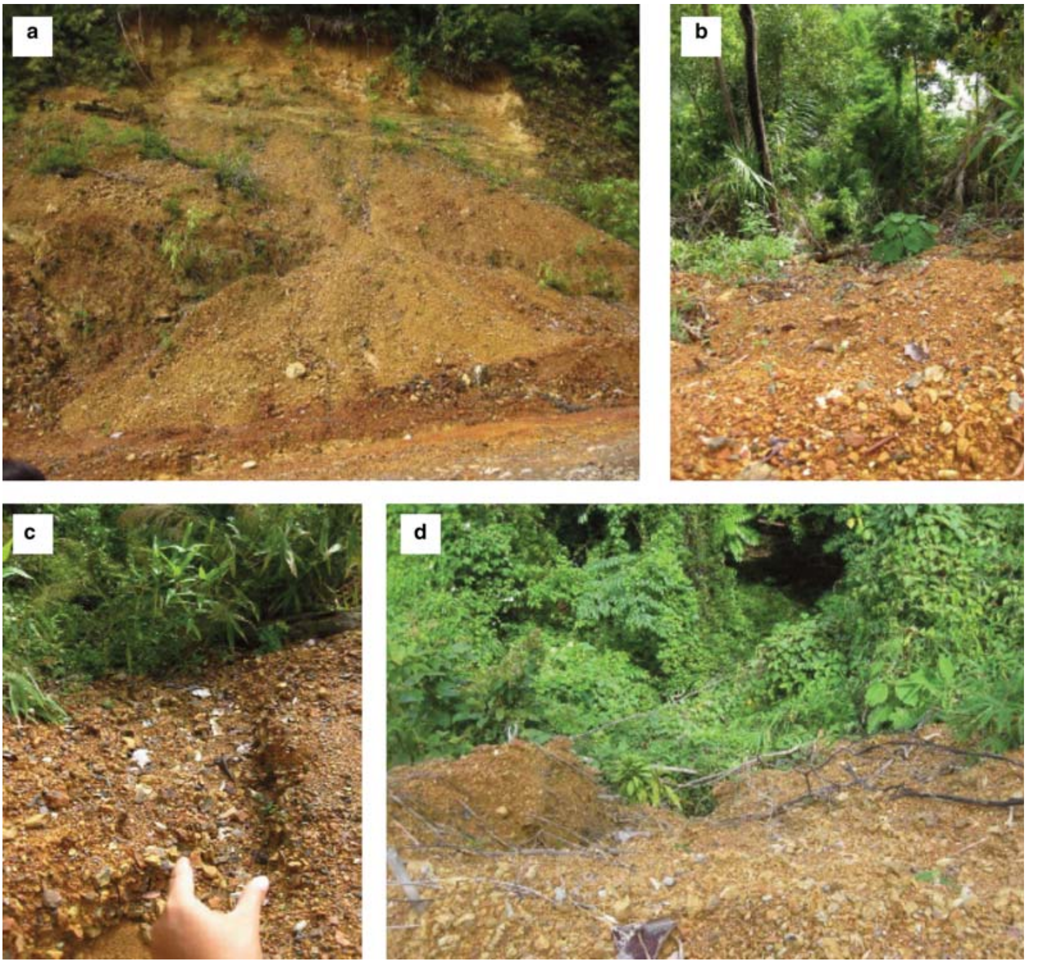

Fig. 4. Slope failures and gullies on the Ao Jak Road: (**a**) landslide along a cut-slope; (**b**) debris flow on a fill-slope; (**c**) sliver failure in fill-slope material; and (**d**) gully formation from overland flow incising a rill on unconsolidated fill-slope material.

fan-shaped talus slope at the base (Fig. 4a). Because most landslides occurred on cut-slopes, mobilized material was often deposited on the road surface or carried across the road and deposited on the fill-slope.

The four debris flows that accounted for 389 m^3 of sediment all occurred on the fill-slope (Table 2; Fig. 4b). These rapid mass-wasting features are characterized as a liquefied mass of sediment flowing down-slope with no scarp at the head of the failure. Sliver failures accounted for only about 40 m^3 of material mobilized (Fig. 4c). Both debris flows and sliver failures occurred on relatively steep slopes of 30°– 45° (Fig. 5). The 10 measured gullies originated from rills that were incised by concentrated overland flow (Fig. 4d). They occurred across a wide range of slopes (15°–40°); and they mobilized, on average, only about 6 m^3 of material each (Fig. 5).

The estimated volume of material mobilized by nine cut-slope landslides was 2136 m^3, compared with 528 m^3 removed by 19 fill-slope failures and gullies (Table 2). Landslides, in particular, occurred on the unstable, oversteepened cut-slopes. In contrast, debris flows occurred exclusively on fill-slopes, where failure of unconsolidated material was triggered by the inflow of concentrated overland flow together with gravitational stresses on the steep unconsolidated slopes. Although numerous fill-slope failures were present, the volume of mobilized material was limited by the availability of unconsolidated material. Despite the disparity in the number and severity of degradation features above and below the road, all collectively threaten

Table 2. *Summary of number (n), slope, and volumes of the failures and gullies on cut- and fill-slopes*

Type	*n*	Hill-slope gradient (°)	Total volume (m^3)	Cut-slope (*n*)	Fill-slope (*n*)	Cut-slope volume (m^3)	Fill-slope volume (m^3)	Mean volume (m^3)	Sediment yield (Mg ha^{-1})
Landslide	11	41 ± 4	2178	9	2	2136	42	198 ± 344	7757
Debris flow	4	37 ± 5	389	0	4	0	389	97 ± 72	1385
Sliver failure	3	37 ± 6	39	0	3	0	39	13 ± 6	139
Gully	10	31 ± 8	58	0	10	0	58	6 ± 9	207
Total	28	34 ± 7	2664	9	19	2136	528	95 ± 229	9488

n is the number of measurements made; gradient and mean volume are the mean ± 1 SD; all other values are totals. Sediment yield was determined assuming that the bulk density of material removed was 1.3 Mg m^{-3}; the mean width of the 0.5 km stretch of road was 7.3 m.

the access and longevity of the road – although the road was still passable at the time of observation. Furthermore, gully erosion and slope failures were contributing to other environmental problems, such as sedimentation in down-slope residential areas and potentially sensitive coastal ecosystems (e.g. coral reefs).

The total erosion rate from the measured slope failures and gullies along the 0.5 km section of the Ao Jak Beach Road was nearly 9500 Mg ha^{-1} $year^{-1}$, with the majority of this being associated with landslides (Table 2). This estimate was based on a mean road width of 7.3 m for the 0.5 km stretch of surveyed road. Although our assessment was carried within the first year following widening and we would expect the risk of additional failures to eventually reduce with time, secondary failures involving the remobilization of material from prior failures may still occur in the future (Sidle *et al.* 2011). However, the rate is a lower-bound annual estimate because it was determined for a period of time that did not include the four wettest months of the monsoon rainy season. It also does not include on-surface road erosion, which could not be quantified accurately.

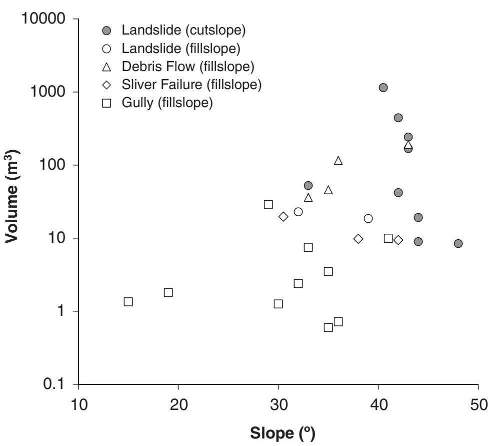

Fig. 5. Relationship between failure type, location (cut-slope or fill-slope) and the total volume of material mobilized (Table 2). Cut-slope landslides, which mobilized the most material, typically occurred on the steepest slopes (filled circles).

The high value found at Ao Jak was similar to the 9600 Mg ha^{-1} $year^{-1}$ rate reported for a 23.5 km stretch of road in Yunnan Province, China (Sidle *et al.* 2011). However, the rate is much lower than the maximum value of a severely affected stretch of road in the Yunnan study (33 000 Mg ha^{-1} $year^{-1}$), which was the highest landslide rate ever reported along roads.

Recommendations

To be effective tsunami evacuation corridors, such roads are often constructed in rugged terrain because of the need to rapidly transport people to higher elevations. In all cases of secondary road building, the location of the road must be carefully determined in order to avoid particularly unstable locations, paying close attention to unstable site indicators (Sidle *et al.* 1985). The route should also be evaluated by a geotechnical engineer or engineering geologist; and construction should follow recognized guidelines (e.g. Kellar & Sherar 2003). If not properly located, planned and constructed, as is often the case in rural remote areas in SE Asia, these roads may either fail completely or restrict access owing to the chronic sedimentation resulting from the unstable conditions. Furthermore, road-related landslides themselves pose a separate hazard to travellers (Sidle *et al.* 2011).

Cutbanks can fail when roads are excavated into steep hillslides, especially where bedrock dips parallel to the slope or where it is highly fractured or jointed (Sidle & Ochiai 2006). Slope failures also occur because of the disruption of equilibrium forces within the hill-slope following construction or because concentrated water is discharged onto unstable slope segments (Sidle & Ochiai

2006). Where possible, roads should not cut into steep and unstable slopes because of the risk of destabilizing the hill-slope. Our measurements showed that the largest volume of material came from cut-slope failures, and that these features often trigger fill-slope failures. Thus, consideration must be given to constructing cut-slopes at stable angles or in more stable substrate, based on the geotechnical properties of the hill-slope materials. For example, for the fractured sandstone found along the Ao Jak Road, a proper slope ratio (horizontal:vertical) would be 1:1–1.5:1 (Keller & Sherar 2003). Cut-slopes may also need to be stabilized with rock buttresses, gabions or mechanically stabilized earth structures (Keller & Sherar 2003). However, expensive mechanical stabilization structures along such secondary roads are generally prohibitively expensive, particularly in developing nations.

Fill-slope failures, such as those observed along the Ao Jak Road (Fig. 5), may be avoided by utilizing full bench construction when slopes exceed 30°–35°. This would require moving some excavated material offsite, rather than simply casting it down the hill-slope. If full bench construction is not possible, a series of small benches could be constructed. Fills should be properly compacted; and retaining structures, reinforced fills and mechanically stabilized earth structures can be utilized to maximize stabilization (Keller & Sherar 2003).

The frequency and intensity of slope failures can generally be reduced by preventing the build-up of positive pore-water pressure through adequate drainage of interflow and surface water to geologically stable locations (Sidle & Ochiai 2006). In addition, the removal of protective vegetation should be avoided to help limit the generation of concentrated overland flow that may erode the fill-slope or undercut the cut-slope (Montgomery 1994). Concentrated road runoff is common in mountainous terrain: it may be generated by the interception of subsurface flow by the cut-slope or initiated on the consolidated road surface as an excess infiltration process during most rainfall events (Ziegler *et al.* 2001, 2007).

The creation of a berm on the outside edge of the road should be avoided, as these features have the tendency to concentrate runoff, thereby increasing the likelihood of slope failures or gullying when the flow is finally discharged onto the hill-slope. On slopes exceeding 6°–7°, in-sloped or crowned roads with cross drain culverts, placed at appropriate distances, would help eliminate the development of high volumes of concentrated overland flow on the road surface (Keller & Sherar 2003). Ideally, inside ditches should be lined to prevent incision. Properly designed outlets with rock protection should be located on the fill-slope side to prevent gullying and debris sliding (Sidle 1980). In most cases, the drainage of runoff directly onto the fill-slope should be avoided.

Conclusion

Evacuation roads serving remote coastlines are problematic in the sense that the immediate success of reducing vulnerability is short-lived if slope failures and surface erosion degrade the road quickly following construction. Given the importance of secondary roads as evacuation routes, more attention is needed to ensure that proper location and design are integral components of tsunami vulnerability reduction and preparedness efforts. Poor road design often leads to chronic degradation that requires substantial maintenance. Steep grades, which are desirable to gain elevation rapidly to escape tsunami surges, are highly susceptible to landslide erosion. Deep cuts into unstable bedrock should be avoided whenever possible. Special attention should be given to road drainage in wet, unstable areas; and drainage water should be routed away from these and other potentially unstable sites down-slope of the road. In some locations, it may not be sensible to rely solely on low-maintenance roads for evacuation – for example, remote coastlines that are secluded by rugged terrain. In such situations other safety measures may be more appropriate, such as the construction of tsunami-proof evacuation structures; however, these types of interventions are prohibitively expensive for developing nations.

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